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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

FORECASTING TROPICAL CYCLONE RECURVATURE USING AN EMPIRICAL ORTHOGONAL FUNCTION REPRESENTATION OF THE SYNOPTIC FORCING

BY

Thomas D. Lage

December 1982

Thesis Advisor: R. L. Elsberry

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Seven forecast aids used by Joint Typhoon Warning Center (JTWC) Guam, were tested for ability to forecast tropical cyclone recurvature at 24, 48 and 72 h. Using the skill scores described above for the 1979-81 typhoon seasons, performance indicates large annual variations of skill between the models.

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Forecasting Tropical Cyclone Recurvature Using an Empirical Orthogonal Function Representation of the Synoptic Forcing

by

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Lieutenant, United States Navy
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Submitted in partial fulfillment of the requirements for the degree of

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December 1982

ABSTRACT

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I. INTRODUCTION

Tropical cyclone recurvature is one of the most difficult events to forecast for even the most experienced forecaster. The ability to forecast recurvature correctly could annually save both the military and civillian communities millions of dollars, thousands of man hours and the lives of many victims. There are few reliable rules that the tropical cyclone forecaster can follow for forecasting recurvature or non-recurvature in either the near and the extended time frames. Riehl and Shafer (1944) were among the first to summarize guidelines for forecasting recurvature of Atlantic tropical cyclones. Riehl and Shafer defined recurvature as "any major alteration of a storm track" which is quite non-descript. Riehl and Shafer listed several factors affecting tropical cyclone motion, including the effects of the upper-level winds and the interaction with troughs in the westerly flow to the west of the tropical cyclone. They also described various synoptic situations to assist the forecaster in predicting the storm path. The Joint Typhoon Warning Center (JTWC) Guam defines recurvature as

"The turning of a tropical cyclone from an initial path toward the west and northwest to the north then northeast"

which is also quite non-descript.

More recent studies by George and Gray (1977), Chan, et al (1980) and Shaffer (1982) have shown that the tropical cyclone motion is largely dependent upon the surrounding steering flow represented by height/temperature fields.

The purpose of this study is to use a simple representation of the synoptic forcing by Empirical Orthogonal Functions (EOF's) plus persistence-related variables to predict tropical cyclone recurvature or non-recurvature. The time increments of 36, 54 and 72 h for forecasting recurvature were selected for several reasons. First, a minimum time period of 36 h was thought to be of greatest value and to provide the most confident forecast for the shore establishment, air wing squadrons and ships presently in port. Secondly, The upper-air soundings are transmitted to Fleet Numerical Oceanography Center (FNOC) by approximately 3 h after 00/12 GMT. These soundings are used to generate the 12-hourly forecasts of the 500 mb heights (in this case). These generated fields would be available to Joint Typhoon Warning Center (JTWC)

Guam prior to the next warning at approximately 6 h after 00/12 GMT. The computer program to decompose the D-value fields (deviations from the standard atomsphere geopotential) into the eigenvectors (EOF coefficients) and compute the persistence statistics, would take at most a few minutes, and could actually be done on a hand held calculator (Shaffer, 1982). This would make the warning time increments equal to 30, 48 and 66 h if the forecast technique makes use of the analyzed and forecast geopotential height fields. This time delay problem could be partially eliminated by using the previous 12-h forecast fields to define steering, which would permit the technique to be available at the time JTWC prepares their forecast at 00/12 GMT. It is believed that little effect would be apparent for the shorter forecast periods, although there would likely be a larger impact on the extended time period forecasts.

II. EOF ANALYSIS OF SYNOPTIC FORCING APPROACH TO RECURVATURE

This research is a sequel to a synoptic map type scheme of Brown (1981) and an EOF representation of the synoptic forcing to predict tropical cyclone motion in the western North Pacific Ocean by Shaffer (1982). The data fields and selection of storm criteria (see descriptions by Brown, 1981; Shaffer, 1982; and Shaffer and Elsberry, 1982) are exactly the same in all three studies. A short summary of the fields and criteria follow.

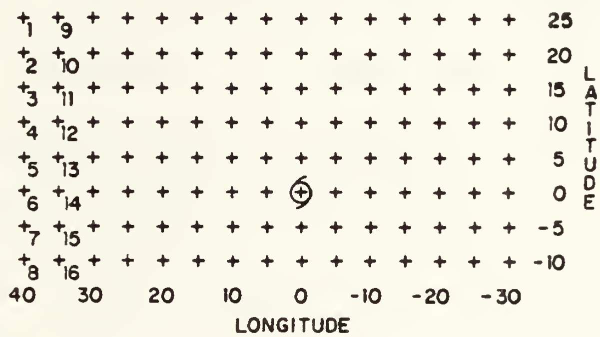

Figure 1. Grid Arrangement Used in Statistical -Climatological Track Prediction.

The 500 mb D-values are extracted on a movable 120-point grid (Fig. 1) over 35° in latitude and 70° in longitude with a 5° increment. The tropical cyclone is always centered at grid point 70 which is 10° from the southernmost boundary and 40° from the western boundary. This choice is made to include both a portion of the mid-latitude flow characteristics and a smaller section of the more uniform tropical height fields to the south of the storm. The movable feature is incorporated to minimize the seasonal variation that would occur if the grid was stationary. The earth's curvature (convergence of the meridians) is not included over the grid but could be easily added for operational use. The D-values on the standard 63 x 63 grid from the FNOC archives are deviations from the standard atmosphere geopotential and are fitted to the 120 point grid by a Bessel linear interpolation scheme.

Requirements for tropical cyclones to be included in this study are:

- The tropical cyclone must be of at least tropical storm intensity (>17 m/sec) and be located to the west of 180°;

- The cyclone must exist at tropical storm intensity for at least 30 hours as analyzed by JTWC (Guam);

- The cyclone must be located between 10°N and 25°N (This is done to prevent the grid from entering the southern hemisphere and to avoid possible problems arising from the convergence of the meridians at higher latitudes);

- The storms must exist at 00/12 GMT for the scheme to be able to use the corresponding FNOC data analyses;

- Each storm observation included must have 36 hours between a prior observation of the same storm to insure pseudo-independence within the sample. This very important restriction insures that the statistical results are unbiased.

One approach to assess spatial variations in geophysical fields is through the use of Empirical Orthogonal Function (EOF) analysis (also known as Principal Component analysis). EOF analysis may be applied to any multi-dimensional data set to separate signal from noise, and identify significant spatial correlation patterns (Hotelling (1933); Kutzbach (1967); Morrison (1967); Barnett (1978); Richman (1980); Shaffer (1982) and others). For geophysical use, the data are placed on the moveable grid with each grid point representing a dimension in space. The data are represented as an MxN matrix, with M the number of grid points, and N the number of data cases. Each column of this matrix represents a single realization of the observed geophysical field. An MxM matrix R is then formed by multiplying the data matrix by its transpose. The form of R depends upon the form in the initial data matrix, but is generally, either a covariance or correlation matrix of the grid points. If one wishes to give equal weighting to each grid

point, the correlation matrix is formed. If, on the other hand, the desire is to give greatest weighting to those dimensions (grid points) with the largest univariate variation, the covariance matrix is formed.

The choice of correlation versus covariance matrix is critical for meteorological fields which cover a large spatial domain. For example, in analyzing geopotential fields, mid-latitude grid points have much greater variability than tropical grid points. If the aim is to focus on mid-latitude features, the covariance matrix form of R is preferable. If, on the other hand, the wish is to determine variability patterns over the entire domain, the correlation matrix form of R is favored. The correlation matrix approach mutes the EOF response in higher variability regions (mid-latitudes), while amplifying the response in regions of lower variability. Both approaches were tested in this study. With the covariance matrix approach, the total explained variation in the D-value fields for the first 10 eigenvectors was more than 94%, which was 9% greater than the correlation eigenvectors. Regression analyses from the covariance method were shown to be inferior to those from the correlation method. Thus, the correlation matrix method is used in this study.

After forming the matrix R, minimization of the total variability leads directly to the eigenvalue problem (Morrison, 1967). The eigenvector associated with the largest eigenvalue is the single vector, out of all possible vectors in space, that minimizes the summed variation (squared) of all of the observation vectors in M space. Furthermore, this eigenmode explains exactly

$$\frac{\lambda_1}{\sum_{i=1}^{M} \lambda_i}$$

of the total variation in the observations, where λ is the eigenvalue of the ith mode. Since the trace of a correlation matrix is identically equal to the order of the matrix, the percent of total variation explained by any eigenvector is simply

$$\frac{\lambda_i}{\sum_{i=1}^{M} \lambda_i}$$

The elements of each eigenvector may be loosely interpreted as the multiple correlation of the corresponding grid point with all other grid points, simultaneously. The exact meaning of the eigenvector elements (loadings) is given by Morrison (1967).

The aim of this project is to investigate spatial variation structures of analyzed 500 mb D-value fields for the western North Pacific Ocean. Therefore, we choose the correlation matrix approach. The initial step in data processing is to point-normalize the data. Specifically, we use

$$\text{Dbar}(i) = \frac{1}{N} \sum_{j=1}^{N} D(i,j)$$

$$D^*(i,j) = \frac{D(i,j) - \text{Dbar}(i)}{\left[\sum_{j=1}^{N} \frac{(D(i,j) - \text{Dbar}(i))^{**2}}{N-1}\right]^{\frac{1}{2}}}$$

where j is the map (case) index and i is the grid point index. Thus, D* (i,j) is simply a normally distributed random variable, with a mean at each grid point over all maps of zero and a variance of 1. This allows an equally-weighted, grid point interpretation of the eigenvectors. For this study, the data analysis was completed using the 500 mb fields only.

The data consist of D-values of geopotential, (the difference between the observed geopotential and the standard geopotential, so that a positive D-value

corresponds to higher than standard geopotentials), in meters. EOF analysis was performed for 120-dimension space (8x15 grid) in Fig. 1. Examples of the first 9 EOF eigenvectors (correlation case) are shown in Fig. 2. It must be stressed that the negative of the pattern shown in these figures is also a solution to the problem. (For examples of 700mb and 850mb eigenvectors see Shaffer (1982).)

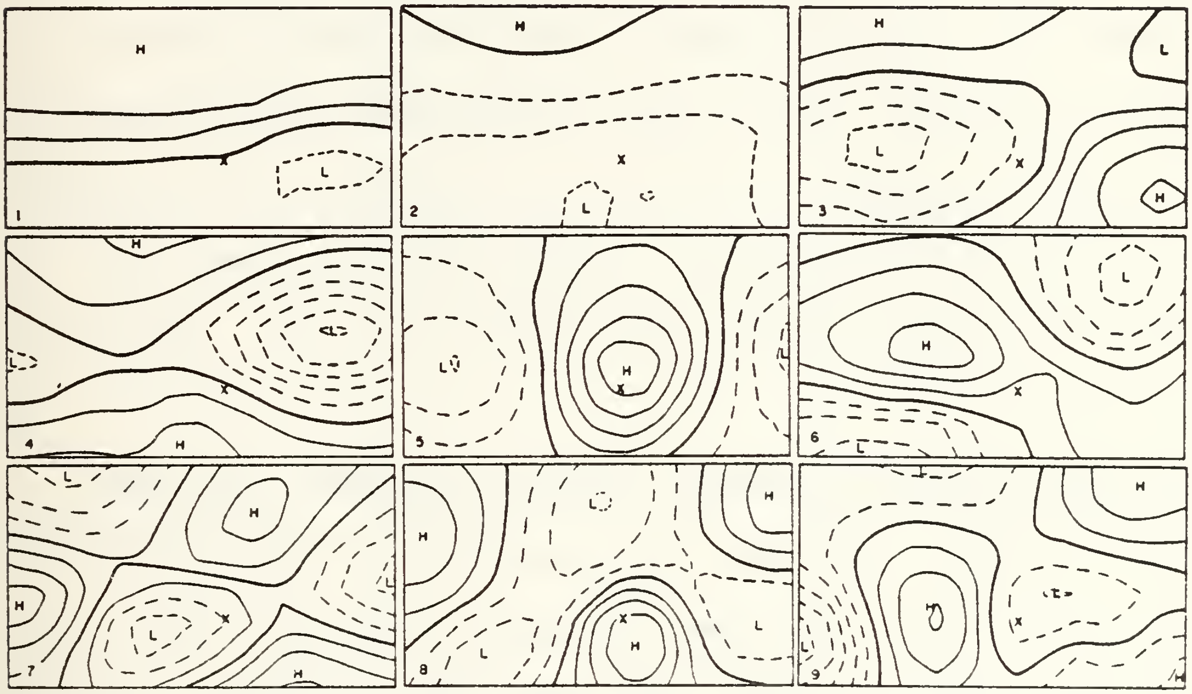

Figure 2. Eigenvectors 1-9 Multiplied by 100. The X Indicates the Location of the Tropical Cyclone, Grid Point 70.

The number of eigenmodes to retain in each case is determined by comparing the eigenvalues of the analyzed

geopotential fields with the eigenvalues of a Monte Carlo simulation of random fields as used by Preisendorfer and Barnett (1977). The eigenmodes retained are those that are larger than the random eigenvalues plus 3 standard deviations. By using this approach we are 99% confident that the only eignvectors retained are those containing actual signal, and that we are discarding noise only. Using this selection procedure, the actual number of significant eigenvectors (EOF's) retained is limited to 10. This number of EOFs explains approximately 85% of the variation in the fields. Table I outlines the increase of explained variance as the number of significant eigenvectors retained is increased. Fig. 3 is the graphical representation of Table I.

The total sample of the 504 storms during the 1967 to 1976 time period is divided into a dependent sample of 454 cases and a 50-case independent sample for use as the test sample. This is the identical sample of 50 randomly selected independent storms that Shaffer (1982) tested for displacement forecasts. Shaffer (1982) and Shaffer and Elsberry (1982) showed that for this independent sample of tropical cyclones, the forecast error from a technique based

TABLE I

Eigenvalues and Cumulative Percent Explained Variance of the Normalized D-value Fields at 500 mb. (Shaffer,1982)

Mode	Eigenvalue	Explained Variance
1	39.86	33
2	21.60	51
3	9.29	59
4	7.43	65
5	6.08	70
6	5.29	75
7	4.00	78
8	3.13	81
9	2.49	83
10	2.11	85
15	1.03	91
20	.58	94
40	.11	98
60	.04	99
120	.00	100

on an EOF representation of the synoptic forcing is decreased by an average of 17% when compared to the official JTWC (Guam) forecast error.

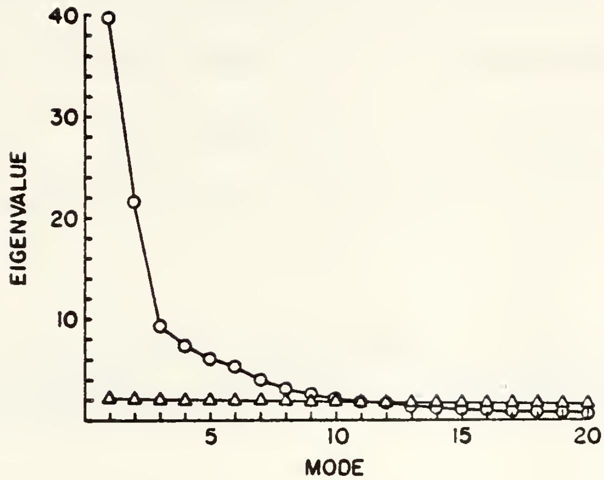

Figure 3. Eigenvalues of the 500 mb D-value Fields (circles) and the Monte Carlo Generated Eigenvalues (triangles) Based on 100 Simulations of Random Data.

III. DEFINITION OF RECURVATURE

The definition of a recurvature case can be thought of as a set of restrictions based on the observed track of the tropical cyclone. The definition of recurvature that is used in this research is that described by Leftwich (1978, 1982):

> "Recurvature is a net displacement northward of 315° during the forecast period or the attaining of northeastward motion during the 12 hours prior to the end of the forecast period".

Storms are not considered if their past 12 hour motion is to the east. A graphical description of recurvature and non-recurvature cases is given in Fig. 4.

Some of the cases present rather difficult forecast situations. Figure 5 depicts Typhoon Trix (initial position at 00GMT 21 August 1971), which for the initial 36-h period would be considered to have recurved, whereas for the 54- and 72-h period it would be considered as a non-recurvature case. Figure 6 depicts Typhoon Polly (initial position at 12GMT 29 August, 1974), which for the 36-h period is considered to have recurved, but then moves westerly to a 54-h position which is considered as having not recurved,

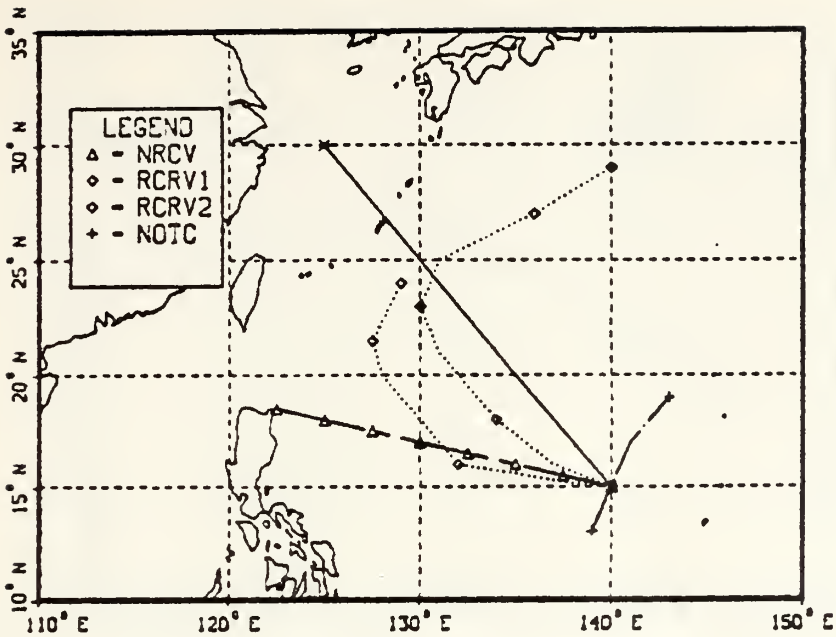

Figure 4. Examples of Idealized Recurvature (1,2), Non-recurvature (3) and a Not Considered Case (4)

and finally moves north-northwest to be considered as a recurvature case at 72 h. Typhoon Cora (initial position of 12GMT 02 October 1975) shown in Fig. 7 is an example of a recurvature case at all three periods, whereas Typhoon Alice (initial position at 12GMT 16 September 1975) in Fig. 8, is a non-recurvature case for all three periods. Typhoon Anita (shown in Fig. 9) would not be considered for the 12GMT 22 July to 00GMT 23 July initial positions due to the eastward motion of the tropical cyclone, but would be considered for the 12GMT 23 July to 00GMT 24 July period.

A summary of the recurvature statistics for the 504 storm sample is given in Table II. The 6 h recurvature

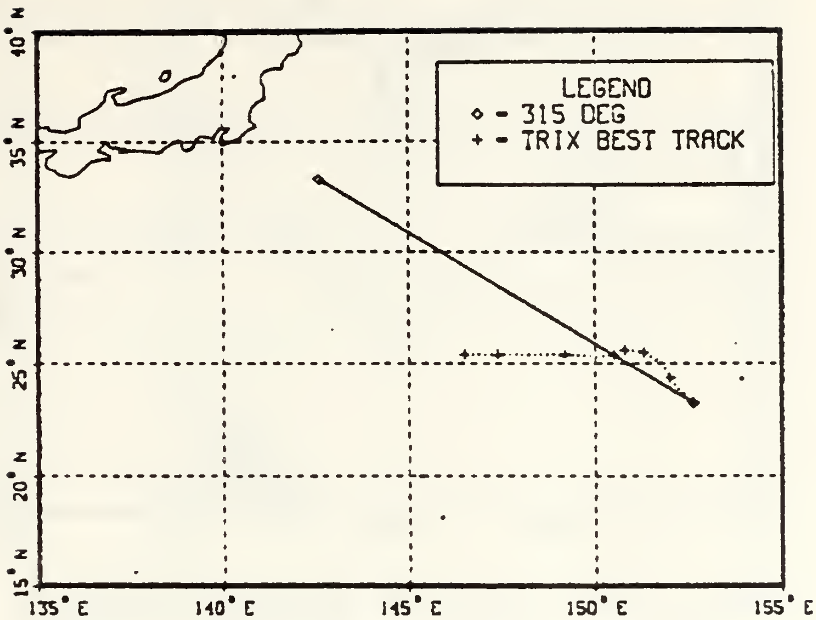

Figure 5. Typhoon Trix Case Illustrating an Apparent Recurvature Case at 36 h, and Non-recurvature at 54 and 72 h

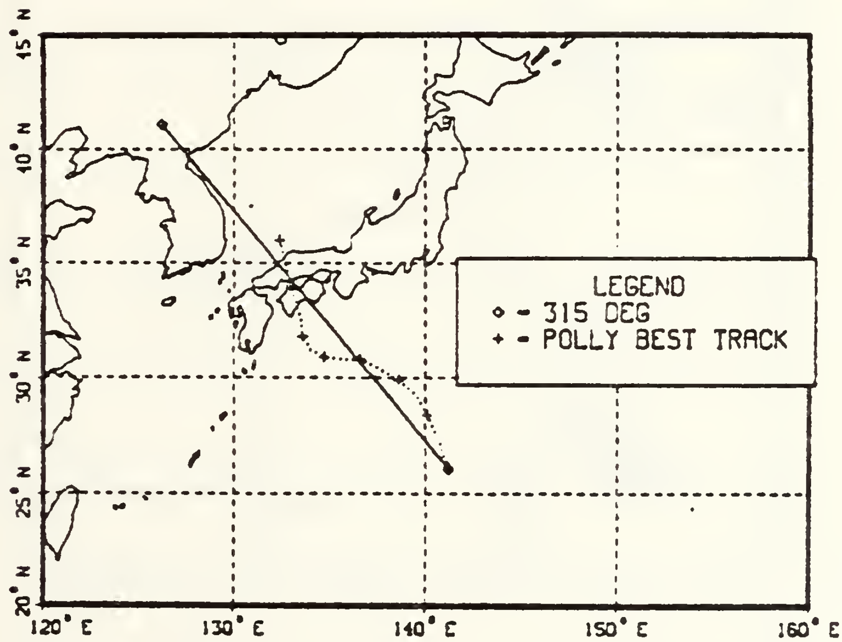

Figure 6. Typhoon Polly Case Illustrating Recurvature at 36 and 72 h and Non-recurvature at 54 h

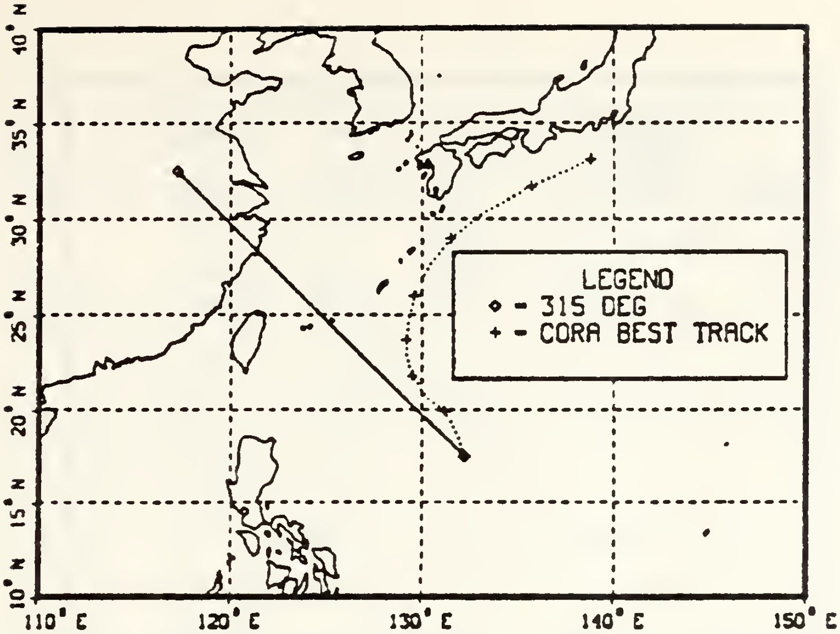

Figure 7. Typhoon Cora Case Illustrating a Common Recurvature Case

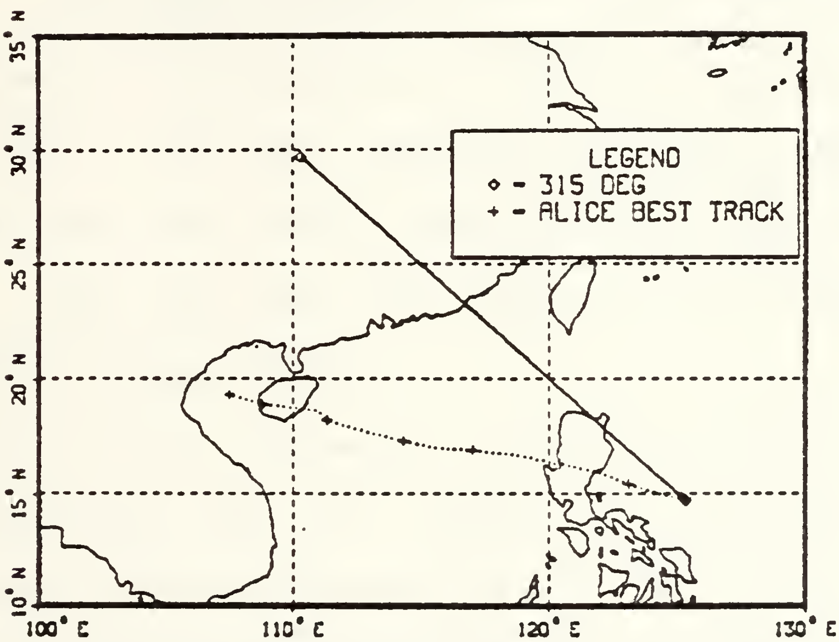

Figure 8. Typhoon Alice Case Illustrating a Non-recurvature Case

statistics were obtained in the same manner as defined earlier, except that the motion during the past 6 h was used

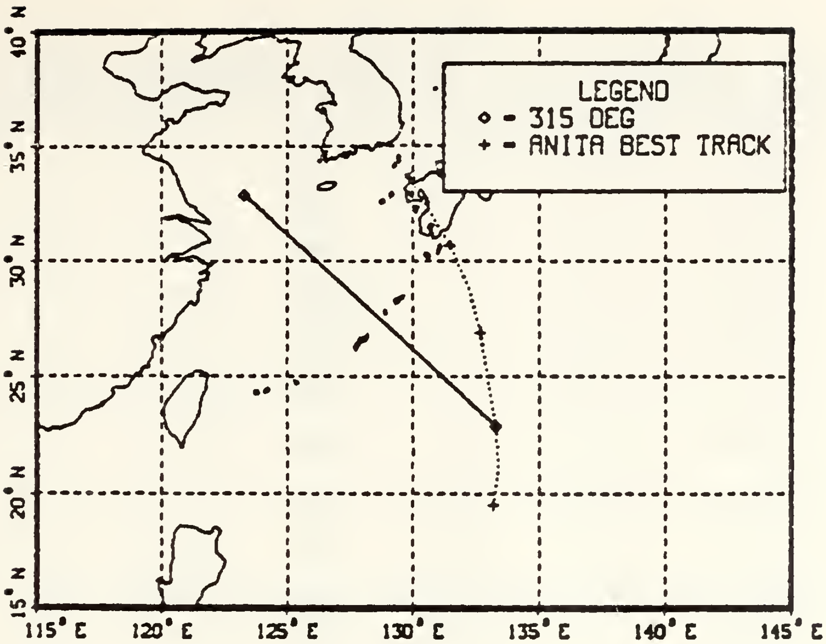

Figure 9. Typhoon Anita Case Illustrating the Exclusion of the 12GMT 22 July to 00GMT 23 July Periods Due to the Eastward Motion

for the second consideration for recurvature vice the past 12 h motion. All past meridional and zonal motions were obtained from the warning positions of each individual storm. This was done to simulate actual operational conditions (Shaffer, 1982).

A graph of the recurvature statistics shown in Table II is presented as Fig. 10. There is a slow increase of probability of recurvature with time. This increase may be explained by the following reasoning. A tropical cyclone in its developmental stages is more often in the easterly trade wind regime and moving west of northwest (non-recurver as

TABLE II

Number of Recurving (rcv), Non-recurving (nrcv), No History (nohist), Not Considered (notcon) and the Probability of Recurvature (prob) for the 504 Tropical Cyclone Sample

tau	rcv	nrcv	nohist	notcon	prob
06	131	234	0	139	.359
12	125	240	0	139	.342
18	130	235	0	139	.356
24	134	231	0	139	.367
30	135	230	0	139	.370
36	158	196	22	128	.446
42	119	169	115	101	.413
48	125	163	115	101	.434
54	133	154	116	101	.463
60	133	139	142	90	.489
66	96	111	230	67	.464
72	103	104	230	67	.498
78	107	100	230	67	.517
84	99	87	254	64	.532

defined). As the tropical cyclone intensifies and moves to higher latitudes, it begins to interact with the mid-latitude westerlies and therefore is more likely to recurve. Cheng-Lan and Sadler (1982) describe the most frequent track of a recurving tropical cyclone as "a regular clockwise parabola". That is, as the tropical cyclone moves westward it also moves northward, with a greater likelihood of being north of a 315° line from the initial position.

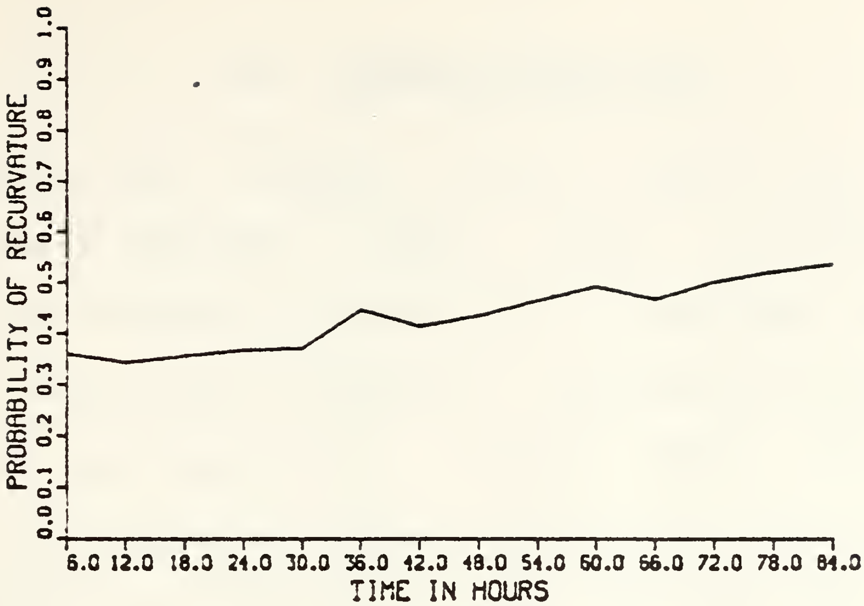

Figure 10. Probability of Recurvature (504 Case Sample Climatology)

The statistics contained in Table II and Fig. 10 are designated as the sample climatological probabilities of recurvature. It should be mentioned that the independent sample statistics for recurvature for all time periods are within 7% of the sample average probability, which indicates consistency between the two samples. These values will be used later as a standard for evaluation of various forecast schemes in predicting recurvature at specified time intervals. That is, a scheme will be said to have skill if it predicts recurvature more accurately than the climatological probability.

IV. REGRESSION ANALYSIS

Neumann and Lawrence (1975) demonstrated that a statistical-dynamical model using prognostic and persistence-related variables in a nonlinear regression scheme showed much promise in forecasting Atlantic ocean tropical cyclone motion. Shaffer (1982) also used a statistical-dynamical scheme that used 10 EOF coefficients to represent the geopotential field (analysis time only) and a linear regression scheme to predict tropical cyclone motion. The EOF analysis not only simplifies the representation of the synoptic forcing, it also reduces significantly the cost of producing an accurate and viable forecast.

The importance of the nonlinear terms in regression schemes has been demonstrated by Neumann and Lawrence (1975) and Paegle and Haslam (1982). Although nonlinear terms were included in those studies, economic considerations and the simplicity of application of a linear model led to its adoption in this study.

To test the effect of including EOF coefficients as predictors of tropical cyclone motion, three separate trials for each of the prescribed times were completed. The first test (refered to as PERS) was accomplished using only the persistence-related parameters and the initial latitude and longitude. A description of all potential predictors is contained in Table III. (All latitude and longitude displacements (displ) are in nautical miles.) The second experiment (referred to as EOFS) utilized 10 EOF coefficients and the initial latitude and longitude. The third experiment used a combination of the persistence and EOF predictors and is noted as P&E. It should be mentioned that the cyclone maximum sustained wind speeds at 12, 24 and 36 h prior to the initial observation were also incorporated as possible predictors. This was done in accordance with Riehl's hypothesis (1971) of maximum intensity being associated with recurvature for Atlantic tropical cyclones. However, none of these additional predictors were chosen during the stepwise regression.

The 504 case tropical cyclone sample was analyzed for recurvature as described in Chapter III. A value of 1.0 was assigned to the storms that recurved and a value of 0.0 was

TABLE III

Potential Predictors Used to Develop the Regression Equations for Each of the Three Time Intervals

Potential Predictor Variable Number	Name	Description (Coeficient-Coef)
1	COF1	Eigenvector 1 Coefficient
2	COF2	Eigenvector 2 Coefficient
3	COF3	Eigenvector 3 Coefficient
4	COF4	Eigenvector 4 Coefficient
5	COF5	Eigenvector 5 Coefficient
6	COF6	Eigenvector 6 Coefficient
7	COF7	Eigenvector 7 Coefficient
8	COF8	Eigenvector 8 Coefficient
9	COF9	Eigenvector 9 Coefficient
10	COF10	Eigenvector 10 Coefficient
11	PLAT0	Initial Cyclone Latitude
12	PLAT1	Past 12 hour meridional displ
13	PLAT2	Past 24 hour meridional displ
14	PLAT3	Past 36 hour meridional displ
15	PLAT4	Meridional displ for prior 12-24 hrs
16	PLAT5	Meridional displ for prior 12-36 hrs
17	PLAT6	Meridional displ for prior 24-36 hrs
18	PLON0	Initial cyclone longitude
19	PLON1	Past 12 hour zonal displ
20	PLON2	Past 24 hour zonal displ
21	PLON3	Past 36 hour zonal displ
22	PLON4	Zonal displ for prior 12-24 hrs
23	PLON5	Zonal displ for prior 12-36 hrs
24	PLON6	Zonal displ for prior 24-36 hrs

assigned to the cyclones that had not recurved at the time of interest. A value of 999. was assigned to cyclones that had no history at the time period of interest.

The BMDP stepwise linear regression program screened the dependent data set for storms with past 12 h longitude displacement (PLON1) that was to the east and also tropical storms that had no history. This screening accounts for the different number of cases considered for the regression routine and the climatology cases at the specific time periods of interest (see Table II). The equations at 36, 54 and 72 h (see Tables IV, V, VI below) are derived from a stepwise linear regression using an F - ratio of 4.0. The F-ratio is a test of the significance of the independent variable coefficients in the regression equations. The number of cases of the dependent sample that are selected for each regression period is noted in the corresponding table. The number of cases decreases with time due to the restrictions for inclusion discussed in Chapter II. Of note is that most of the cases at 72 h are a subset of the 54 h data set, which is in turn a subset of the 36 h data set. The R Squared Statistic ,RSQ, (percent of variance in the predictand explained by the regression equation) will be used for discussion of the results.

The linear regression equations produced from the potential predictors of recurvature or non-recurvature are of the form:

$$P(0:1) = a0 + a1X1 + a2X2 + a3X3 + \ldots\ldots + a7X7.$$

Tables IV, V, and VI list the coefficients and variables for each of the three tests generated from the dependent data sets. The number of cases used to generate the coefficients are 259, 206 and 138 respectively.

TABLE IV

Regression Equations for 36 h Recurvature for Each of the Three Methods Tested (Dependent Sample), and Mean Values and the Standard Deviation from the Mean (STD)

	PERS	EOFS	P&E	MEAN	STD
intercept	.1852	-.2871	.5502		
PLAT0	.0167			19.4	5.2 (°)
PLON0		.0054		133.2	12.9 (°)
PLAT2	.0017		.0014	96.4	90.2 (NM)
PLON1	.0031		.0031	-92.6	55.8 (NM)
COF 1		-.0326	-.0215	.81	5.12
COF 3		.0367		-.24	2.89
COF 5		-.0302		.20	2.34
COF 7		.0341	.0299	-.07	1.91
COF 8		.0493		-.20	1.77
COF 10		-.0545	-.0397	-.10	1.48

Each regression coefficient is unique except for the value of PLON1 for the PERS and P&E test at 36 hours. It should

TABLE V

Regression Equations for 54 h Recurvature as Described in Table IV

	PERS	EOFS	P&E	MEAN	STD
INTERCEPT	.4446	.4957	.4873		
PLAT2	.0019		.0014	95.6	86.6
PLON1	.0022		.0016	-93.0	56.6
COF 1		-.0312	-.0252	1.23	4.8
COF 3		.0371	.0237	-.53	2.74
COF 8		.0618	.0465	-.21	1.82
COF 10		-.0514		.05	1.50

TABLE VI

Regression Equations for 72 h Recurvature as Described in Table IV

	PERS	EOFS	P&E	MEAN	STD
intercept	.5487	.5311	.5821		
PLAT4	.0028		.0026	44.1	48.1
PLON1	.0027		.0024	-89.1	52.2
COF 1		-.0324	-.0230	2.02	4.55
COF 3		.0410		-.75	2.77

be noticed that the value of PLON1 must necessarily be less than zero, because a PLON1 greater than zero represents easterly movement, which is considered as having already recurved.

The total number of combinations of predictors and regression coefficients will not be discussed, but several combinations will be mentioned. PLAT2 (past 24 h latitude

displacement) is almost always greater than zero (the exception being trochoidal oscillating storms), and makes a considerable contribution towards recurvature (predictand close to 1.0) especially for large displacements. PLATO and PLONO (initial latitude and longitude) are always greater than zero, with larger values being favorable for recurvature prediction. The coefficient of the first eigenvector (COF 1) has the opposite effect. Physically, the stronger the zonal pressure gradient (large COF 1), the lower the probability of recurvature. The opposite is also true; the probability of recurvature is higher for extremely weak zonal pressure gradients as illustrated in Fig. 11.

Analysis of the sample mean values of the coefficients of EOF 1 (assuming a normal distribution about the mean) indicates that the number of recurving tropical cyclones would be less than the number of non-recurving storms. For example, the number of recurving storms at 36 h (Table II) is 158 and the number of non-recurving storms is 196. The coefficient of EOF 5 is also quite interesting. The more the EOF 5 pattern describes the synoptic forcing (the larger the value of COF 5), the more likely the storm will not

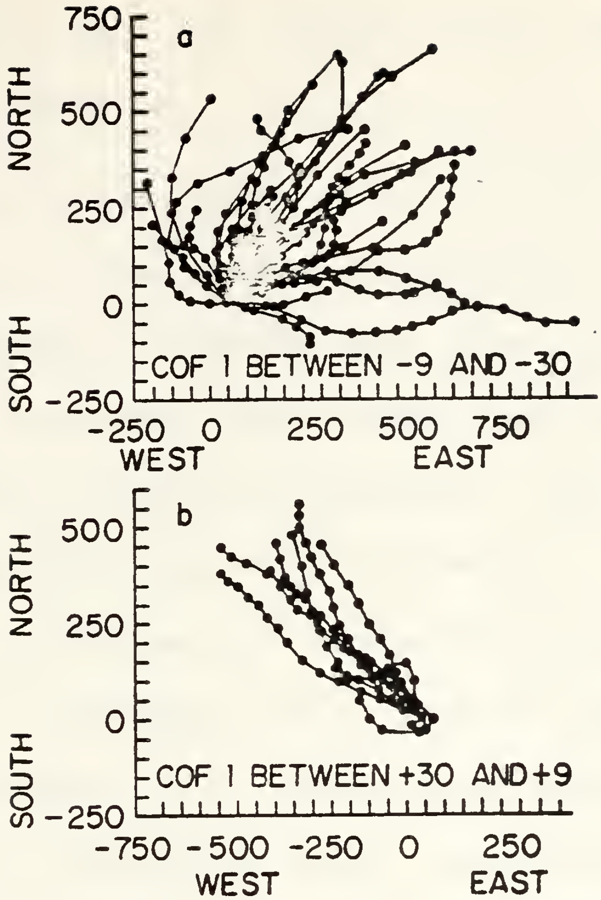

Figure 11. Storm Tracks Relative to the Initial Position for All Storms with an Orthogonal Coefficient 1 that is: (a) Between -9 and -30; or (b) Between +9 and +30. Each Cross Indicates a 12-h Displacement (Shaffer, 1982)

recurve. The converse is also true in that the stronger the inverse or the negative of the pattern (a strong shortwave between two ridges), the more likely the cyclone is to recurve.

This is by no means a complete discussion of all the possible 54 linear combinations of predictors, coefficients and their inverses. It does show how a simple combination

of EOF patterns can be applied with straight-forward meteorological reasoning.

A. 36 H REGRESSION CASE ANALYSIS

As expected, the predictors selected for the PERS regression analysis included the past 12-h longitude displacement, the past 24-h latitude displacement and the initial latitude. Simple extrapolation techniques do well for these relatively short-time forecasts. The longitude displacement over the past 12 hours reduces the variance in the predictand (increases RSQ) slightly more than the latitude displacement. The selection of initial latitude as a predictor is consistent with the variation of the probability of recurvature with time (and therefore latitude for an idealized storm track) as discussed in Chapter II. The total explained variance of the predictand for the persistence-related predictors was 29.2%.

The individual EOF predictors reduce less of the variance than the persistence-type predictors (Table VII). Notice that eigenvector 1 (which is an indicator of the strength of the zonal pressure gradient and large global wave number) causes the largest reduction in the variance of the predictand. The remaining five eigenvectors that were

selected are indicative of smaller scale forcing features, and reduce the variance of the predictand much less that the first eigenvector. Shaffer (1982) indicated the possibility of weak northwest motion (or southeast motion for the inverse mode) would be associated with eigenvector 7 and a strong meriodional forcing being associated with eigenvector 3. Of special interest is eigenvector 5. Although the reduction in variance associated with this eigenvector is small, its inverse pattern appears similar to a strong short wave in the westerlies which could advect the storm northward. The last predictor selected, the initial longitude, again is consistent with the variation of the recurvature probability with time. The total of the explained variance for the EOFS test was 26.5% , which is 2.7% less than using persistence only predictors.

The selection of predictors for the final test shows a combination of both PERS and EOFS predictors. The largest reduction of the variance occurs with past motion (persistence related) parameters. The strength of the zonal pressure gradient appears as the next most important predictor with smaller scale features (EOFS 10 and 7) contributing small increases to the explained variance. The

total of the explained variance of the predictand is 34.0% which is greater than either the PERS or EOFS methods, but still only a small fraction of the total variation.

Part of the reason that more of the predidictand variation could not be explained may be related to the arbitrary definition of recurvature, e.g. a movement to 320° is recurvature (value 1.0) whereas 310° is not (value of 0.0). When a yes/no decision is applied across a line as in this situation, one cannot expect an explained variance near 100%. The method could still provide useful guidance for the forecaster if the percentage of correct forecasts is higher than other methods available.

The entry of PLATO, and then the subsequent deletion as the EOF information is added, is an indication of overlapping information. Notice (Table VII) that PLATO does not enter in scheme (c) at all.

TABLE VII

Summary of Stepwise Linear Regression Results for 36 h (259 cases) R Squared (RSQ), Increase in R Squared (RSQ Incr) and F to Enter or Remove

a) PERSistence only

Step	Parameter	RSQ	RSQ Incr	F enter	F remove
1	PLON1	.151	.151	45.65	
2	PLAT2	.263	.112	39.06	
3	PLAT0	.292	.029	10.42	

b) EOFS only

Step	Parameter	RSQ	RSQ Incr	F enter	F remove
1	COF1	.121	.121	35.40	
2	PLAT0	.161	.040	12.04	
3	COF8	.187	.026	8.20	
4	COF7	.206	.019	6.04	
5	COF3	.227	.021	6.85	
6	COF10	.243	.016	5.47	
7	PLAT0	.234	-.009		2.94
8	COF5	.248	.014	4.54	
9	PLON0	.265	.017	5.75	

c) Persistence & EOFS

Step	Parameter	RSQ	RSQ Incr	F enter	F remove
1	PLON1	.151	.151	45.65	
2	PLAT2	.263	.112	39.06	
3	COF1	.313	.050	18.54	
4	COF10	.327	.014	5.10	
5	COF7	.340	.013	5.18	

B. 54 H REGRESSION CASE ANALYSIS

The selection of PERS predictors at 54 h (Table VII) are the same as at 36 h (Table VI) except for the deletion of the initial latitude. Had the F-test been set for 3.9 vice 4.0, the initial latitude would have been selected subsequent to PLON1, as was the case for 36 h. At 54 h the latitudinal displacement for the past 24 h decreased the variance of the predictand more than did the past 12 h longitude predictor. These two predictors comprise 16.4% of

the variance of the predictand, which is almost half the value obtained at 36 h. This decrease is not surprising, because simple extrapolation techniques have less validity at 54 h than at 36 h.

The number of predictors selected in the EOFS test decreased to four, compared to seven at 36 h. These four predictors at 54 h are all included within the first five predictors at 36 h. The north/south pressure gradient (EOF 1) again contributed to the largest reduction in the variance of the predictand (see Figure 2). EOF 8 appears to be similar to EOF 5 in that it is associated with a mid-latitude short wave combined with an area of high pressure directly south of the tropical storm. EOF 8 is correlated directly with recurvature as are EOFS 1 and 3. EOF 10 is indirectly correlated with recurvature due to the high pressure area to the northwest of the storm center. The stronger this pattern, the less likely it is that the storm will recurve. The total of the explained variance of the predictand is 19.4% which is smaller than the value for 36 h using EOFS only, but it is larger than 54 h regression using persistence parameters only. This result suggests that synoptic parameters begin to explain more of the motion

at later times than does the extrapolation associated with persistence variables.

The combination of the two types of predictors explain 24.6% of the variance of the predictand. The only EOF predictor that does not appear in P&E is eigenvector 10. The inclusion of the eigenvectors as predictors increased the RSQ amount by 8.2%. The decrease from 34.0% explained variance at 36 h to 24.6% at 54 h was expected due to the likelihood of more tropical cyclone interactions with the synoptic environment.

TABLE VIII

Summary of Stepwise Linear Regression Results for 54 h (206 cases) as Described in Table VII.

a) PERSistence only

Step	Parameter	RSQ	RSQ Incr	F enter	F remove
1	PLAT2	.102	.102	23.26	
2	PLON1	.164	.062	15.06	

b) EOFS only

Step	Parameter	RSQ	RSQ Incr	F enter	F remove
1	COF1	.074	.074	16.20	
2	COF8	.127	.053	12.42	
3	COF3	.170	.043	10.41	
4	COF10	.194	.024	6.03	

c) Persistence & EOFS

Step	Parameter	RSQ	RSQ Incr	F enter	F remove
1	PLAT2	.102	.102	23.26	
2	PLON1	.164	.062	15.06	
3	COF1	.203	.039	9.93	
4	COF8	.230	.027	6.97	
5	COF3	.246	.016	4.15	

C. 72 H REGRESSION CASE ANALYSIS

The selection of predictors for the 72 h prediction includes a new predictor, PLAT4 (latitude displacement for the period 12 to 24 h prior to the initial time). This predictor is inherently positive and therefore adds to the probability of recurvature. The past 12 h longitude displacement is the remaining predictor chosen. The total of the explained variance using these two predictors is 15.0%. Although this is less than half of the value of the 36 h regression, it is only slightly less than the 16.5% obtained for the 54 h regression.

TABLE IX

Summary of Stepwise Linear Regression Results for 72 h (138 cases) as Described in Table VII.

a) PERSistence only

Step	Parameter	RSQ	RSQ Incr	F enter	F remove
1	PLON1	.074	.074	10.84	
2	PLAT4	.150	.076	12.01	

b) EOFS only

Step	Parameter	RSQ	RSQ Incr	F enter	F remove
1	COF1	.076	.076	11.27	
2	COF3	.128	.052	8.03	

c) Persistence & EOFS

Step	Parameter	RSQ	RSQ Incr	F enter	F remove
1	COF1	.077	.077	11.27	
2	PLON1	.132	.055	8.63	
3	PLAT4	.192	.060	9.94	

The EOFS-only regression produced results that explain less of the variance of the predictand than did the

persistence-type predictors. Coefficients 1 and 3 explain 12.8% of the total variance of the predictand, which is almost identical to the value for the first steps of the 54 h regression. However, two different coefficients entered the 54 h regression equation.

The combination of two groups of predictors is again superior to either individual group. At 72 h the north/south pressure gradient is more important than the longitudinal displacements 84 h earlier (PLON1) or the latitude displacement 84 to 96 h prior to the initial position (PLAT4). Use of extrapolation-type methods can not be expected to contribute as much as the synoptic parameters at such long time intervals. As the tropical cyclone moves into the mid-latitudes, persistence is comparatively less useful as a predictor than in the tropics.

The amount of explained variance of the recurvature event decreased with time for each of the three test groups. The superior method (as far as explaining the variability of the predictand) is the combination of persistence-related variables and the EOF coefficients which describe the synoptic patterns. Although the P&E technique consistently explained more of the variance than the other two methods,

further testing is necessary to determine if the EOF predictions are superior to other techniques such as climatology or mere chance.

V. TESTING THE REGRESSION ANALYSIS

Choosing a forecast verification scheme is very important for testing the ability of a regression model or a prognostic method to forecast a specific event. The geophysics community is just one of the many scientific communities that desire an accurate and acceptable method for describing the skill of a given model. Muller (1944) provided a literature survey of 55 short-range weather verification methods that were developed during 1884 to 1943 in six different countries. Muller divided the schemes into two areas: comparisons of the forecasts and observations as a ratio (percentage correct) and verification methods which are compared to chance or climatology, the so-called 'blind' forecasts.

In the early verification studies, the schemes for comparing forecasts with observations had to be simple for the ease of application. Verification methods today compare the prediction skill against some climatological value or to pure chance as a point of reference.

Three skill scores will be discussed: the Heidke Skill Score (HSS), the Brier P-Score (BPS), and the percent of correct forecasts (PCF). The Heidke skill score can be written as:

$$HSS = \frac{VF - C}{T - C}$$

where VF is the number of correct or verifying forecasts of an event (either correctly forecast recurvers (CFR), i.e., predictand is greater than or equal to an assigned climatology probability (Table II); or a correctly forecast non-recurver (CFNR), i.e., the predictand is less than the climatology probability), T is the total number of forecasts made and C is equal to the number of correct forecasts that would be expected from chance. In this test C is always one-half of the total number of forecasts. The HSS would have a maximum value of 1.0 for perfect forecasts and a value of zero when the number of correct forecasts is equal to the number of forecasts expected to be correct by using chance. Negative values occur if the method is inferior to the comparative methods.

The Brier or P-Score has been widely accepted as a method to test probability forecasts. The binary form of the BPS can be written as:

$$BPS = \frac{2}{N} * \sum_{i=1}^{N} (FCST(i) - ACT(i))**2$$

where FCST is the regression equation predictand and ACT is either 1.0 if the storm actually recurved or zero if recurvature did not occur. A perfect BPS is a value of zero and the worst possible forecast would be indicated as 2.0. It is readily apparent that the BPS is actually the mean square error of the set of probabilistic forecasts.

The percent of correctly forecast events (PCF) can be written as:

$$PCF = \frac{CFR + CFNR}{T}$$

where CFR, CFNR and T are the same variables as described earlier.

As discussed in Chapter IV, the predictand values should lie on the continuous interval between 1.0 and 0.0. The unfiltered predictand statistics for both the dependent and independent samples for all periods appear in Table XI.

Values larger than 1.0 (indicative of a strong recurvature signal) and smaller than 0.0 (indicating strong non-recurvature signal) exist as maximum and minimum values. These values outside of the defined range are due to the assumed linear relationship between the predictors. Table XII provides similar statistics for the predictands after values that were more than 1.0 and less than 2.0 were set equal to 1.0 and negative values were set equal to 0.0. Comparison of the dependent and independent samples of both tables indicate that the two sets are quite similar. The different number of cases included in several tests is due to the predictors PLAT2 and PLON1 being excessively large, (purposely assigned flagged values) which causes several predictand values for PERS and P&E to be in excess of 2.0, the upper filter limit.

Tables XI and XII indicate that the variance of the dependent predictand is greater than or equal to the variance of the independent predictands in 15 of 18 comparisons. This is evidently due to the small size of the independent sample.

It also should be noticed that the dependent sample variances are largest at 36 h and decrease in time. In all

dependent data set comparisons, the variance of the P&E test is larger than the other two tests. This is most likely due to the 'signal' of either recurvature or non-recurvature being strongest for this set which includes both persistence and synoptic features. The smaller values of the variance in Table XII, as compared to Table XI, is due to the filtering of the predictands, which is described above.

TABLE XI

Predictand Statistics for the 36, 54 and 72 h Before Filtering. The Number of Cases, Mean, Maximum and Minimum Values (max,min) and the Variance (var) of the Predicted Values for the Dependent and Independent Data Sets are Shown

		Dependent Set			Independent Set		
		PERS	EOFS	P&E	PERS	EOFS	P&E
cases		(349)	(433)	(350)	(48)	(49)	(48)
36 h	mean	.498	.432	.512	.454	.436	.473
36 h	max	1.790	1.550	1.810	1.020	1.290	1.050
36 h	min	-.256	-.243	-.259	-.259	.025	-.191
36 h	var	.120	.083	.151	.096	.063	.084
cases		(271)	(345)	(271)	(43)	(43)	(43)
54 h	mean	.486	.434	.485	.438	.450	.455
54 h	max	1.950	1.390	1.780	.867	.983	.889
54 h	min	-.021	-.151	-.112	-.110	-.082	-.392
54 h	var	.065	.049	.090	.047	.041	.073
cases		(176)	(235)	(176)	(38)	(38)	(38)
72 h	mean	.485	.427	.482	.459	.484	.512
72 h	max	1.360	1.060	1.340	.978	.821	1.070
72 h	min	-.037	.099	-.038	-.048	.121	-.132
72 h	var	.053	.027	.065	.053	.028	.062

The summaries of the HSS which compares the three methods of testing using the climatology probabilities of recurvature for both the dependent and independent data sets are presented in Table XIII. It should be noticed that the

TABLE XII

Predictand Statistics for 36, 54 and 72 h After Filtering as Described in Table XI.

		Dependent Set			Independent Set		
		PERS	EOFS	P&E	PERS	EOFS	P&E
cases		(349)	(433)	(350)	(48)	(49)	(48)
36 h	mean	.486	.427	.488	.466	.430	.479
36 h	max	1.000	1.000	1.000	1.000	1.000	1.000
36 h	min	.000	.000	.000	.000	.025	.000
36 h	var	.088	.069	.099	.082	.054	.075
cases		(271)	(345)	(271)	(43)	(43)	(43)
54 h	mean	.478	.433	.472	.443	.452	.467
54 h	max	1.000	1.000	1.000	.867	.983	.889
54 h	min	.000	.000	.000	.000	.000	.000
54 h	var	.051	.046	.068	.042	.039	.058
cases		(176)	(235)	(176)	(38)	(38)	(38)
72 h	mean	.483	.427	.477	.460	.484	.514
72 h	max	1.000	1.000	1.000	.978	.821	1.000
72 h	min	.000	.099	.000	.000	.121	.000
72 h	var	.049	.027	.057	.052	.028	.057

number of cases in each test does not change from the earlier values.

TABLE XIII

Heidke Skill Score Using the Sample Climatology as a Standard of Comparison for Defining Recurvature Versus Non-recurvature for the Filtered Predictands (as in Table II) A HSS Of 1.0 is Perfect.

	Dependent Set			Independent Set		
	PERS	EOFS	P&E	PERS	EOFS	P&E
36 h	.553	.517	.526	.464	.296	.469
54 h	.505	.422	.565	.442	.536	.440
72 h	.431	.254	.454	.431	.363	.510

The information pertaining to the skill of the HSS in Table XIII must be carefully interpreted. When using the HSS, any predictand that is greater than or equal to a

specific value (in this case a climatological percentage of recurvature for that forecast interval) is given a forecast recurvature value of 1.0. Any predictand that is less than the climatological value is considered to be a non-recurvature case, and is assigned a value of 0.0. These 'newly assigned' predictands are then compared to the actual storm recurvature values. If the forecast and the actual value match, a verifying forecast is tallied (CFR or CFNR is incremented by one).

A graphical comparison of HSS versus a varying climatological value of probability of recurvature (used for comparison) is shown in Fig. 12. The maximum values in the HSS are close to, although not necessarily associated with, the climatological probability values indicated for the three different time periods.

Another point needs to be mentioned concerning the HSS. The climatological probability values for recurvature (Table II) at the specified times should be compared to the means and variances of the predictands shown in Table XII. All three climatological values of recurvature fall within the first standard deviation around the mean in all three tests. With this in mind, one would predict that methods with the

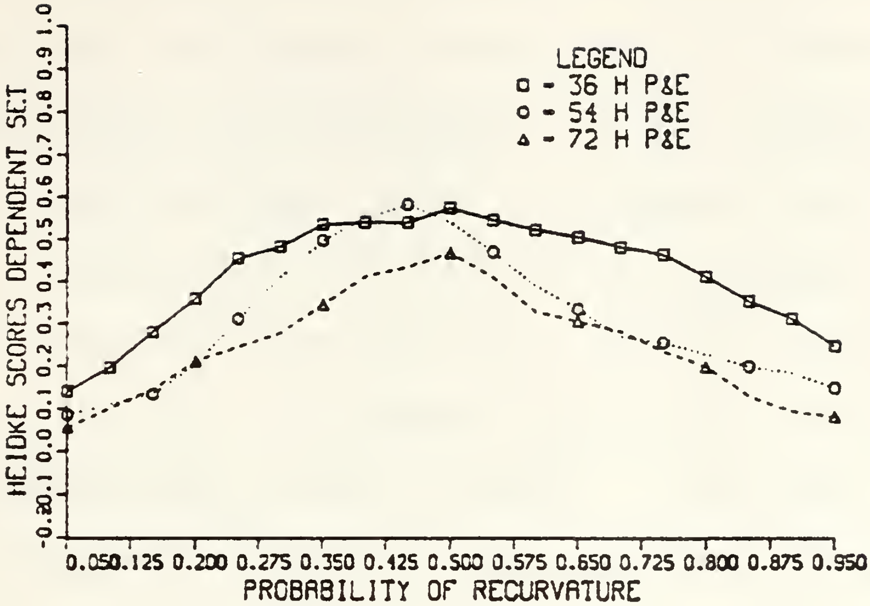

Figure 12. Heidke Skill Scores with the Value of the Predictand from the P&E Equations that is Defined to be Recurvature Varied from 0.05 to 0.95.

smallest variances would have a higher HSS due to the greater probability of being near the climatological value (low signal regime) than in the tails (high signal regime) of the predictand distribution (to be discussed later).

In Table XIII, the combined P&E method produced the highest scores relative to climatology, except at the 36 h period with the dependent set, where the PERS method was best. An indication of the clustering of predictands about the mean appears in the 54 h independent set. The

predictands based only on EOFS have the highest scores relative to climatology at this time, while at both 36h and 72 h the EOFS were inferior to the other two methods. P&E generally showed the highest skill for the independent set, with the exception being at 54 h as discussed above.

The distribution and cumulative frequency of the filtered predictands for the three tests are given in Table XIV, XV, and XVI. An unbiased distribution would have 10% of the observations in each category. This ideal limit is nearly attained at the 36 h time period for the dependent data set. However, biases become more evident for later time periods. The P&E test generally is less biased than the PERS test. Both P&E and PERS are less biased than the EOFS test, which again is an indication of the clustering of the EOF predictands near the mean value.

TABLE XIV

Predictand Distribution and Cumulative Percentage Distribution for 36 h. Cumulative Percentage is in Parens.

	Dependent Set			Independent Set		
36 h	PERS	EOFS	P&E	PERS	EOFS	P&E
.0- .1	36 (10)	38 (9)	41 (12)	8 (17)	3 (6)	5 (10)
.1- .2	37 (21)	51 (21)	31 (21)	0 (17)	5 (16)	3 (17)
.2- .3	34 (31)	70 (37)	42 (33)	5 (27)	6 (29)	4 (25)
.3- .4	35 (41)	69 (53)	40 (44)	8 (44)	6 (41)	5 (35)
.4- .5	50 (55)	47 (66)	42 (56)	4 (52)	12 (65)	9 (54)
.5- .6	32 (64)	43 (76)	31 (65)	8 (69)	8 (82)	8 (71)
.6- .7	33 (74)	33 (83)	23 (71)	4 (77)	5 (92)	5 (81)
.7- .8	32 (83)	26 (89)	22 (78)	3 (83)	0 (92)	3 (88)
.8- .9	16 (87)	16 (93)	23 (84)	6 (96)	1 (94)	1 (90)
.9-1.0	44 (100)	31 (100)	55 (100)	2 (100)	3 (100)	5 (100)

TABLE XV

Predictand Distribution and Cumulative Percentage Distribution for 54 h. Cumulative Percentage is in Parens.

	Dependent Set			Independent Set		
54 h	PERS	EOFS	P&E	PERS	EOFS	P&E
.0- .1	11 (3)	12 (4)	16 (6)	4 (9)	2 (5)	5 (12)
.1- .2	20 (12)	31 (13)	22 (14)	2 (14)	1 (7)	3 (19)
.2- .3	30 (23)	59 (30)	37 (28)	3 (21)	6 (21)	0 (19)
.3- .4	45 (39)	61 (47)	42 (43)	5 (33)	8 (40)	7 (35)
.4- .5	43 (55)	63 (66)	42 (59)	14 (65)	10 (63)	6 (49)
.5- .6	39 (69)	51 (80)	35 (72)	6 (79)	6 (77)	9 (70)
.6- .7	35 (82)	26 (88)	27 (82)	6 (93)	6 (91)	5 (81)
.7- .8	26 (92)	19 (93)	14 (87)	1 (95)	3 (98)	6 (95)
.8- .9	13 (97)	11 (97)	8 (90)	2 (100)	0 (98)	2 (100)
.9-1.0	9 (100)	12 (100)	28 (100)	0 (100)	1 (100)	0 (100)

TABLE XVI

Predictand Distribution and Cumulative Percentage Distribution for 72 h. Cumulative Percentage is in Parens.

	Dependent Set			Independent Set		
72 h	PERS	EOFS	P&E	PERS	EOFS	P&E
.0- .1	6 (3)	1 (.4)	11 (6)	3 (8)	0 (0)	2 (5)
.1- .2	18 (13)	11 (5)	10 (12)	2 (13)	2 (5)	3 (13)
.2- .3	15 (21)	38 (21)	20 (23)	3 (21)	5 (18)	1 (16)
.3- .4	29 (38)	63 (48)	32 (41)	6 (37)	5 (32)	4 (26)
.4- .5	28 (53)	56 (72)	23 (55)	9 (55)	6 (47)	5 (39)
.5- .6	23 (66)	35 (87)	32 (72)	7 (74)	13 (82)	10 (66)
.6- .7	28 (82)	15 (93)	16 (81)	5 (87)	3 (89)	7 (84)
.7- .8	20 (94)	9 (97)	15 (89)	3 (95)	2 (95)	3 (92)
.8- .9	5 (97)	5 (99)	11 (95)	0 (95)	2 (100)	1 (95)
.9-1.0	6 (100)	2 (100)	8 (100)	2 (100)	0 (100)	2 (100)

The Brier P-Scores for the three individual tests and also the BPS for the sample climatology and for chance are given in Table XVII which indicates that each of the three methods is superior to climatology and chance at all forecast times. This is encouraging and is also an indication that the ECF approach of describing the synoptic forcing is a valid approach that merits further

TABLE XVII

P-Score Statistics for 36, 54 and 72 h Dependent and Independent Data Sets After Filtering of the Predictand (A Score of 0.0 is Perfect)

	Dependent Set			Independent Set		
	PERS	EOFS	P&E	PERS	EOFS	P&E
36 h	.308	.348	.297	.390	.454	.383
climo		.502			.490	
chance		.500			.500	
54 h	.367	.409	.340	.401	.393	.368
climo		.500			.504	
chance		.500			.500	
72 h	.389	.451	.378	.443	.441	.417
climo		.500			.500	
chance		.500			.500	

investigation. Neither PERS or EOFS alone show as much skill as P&E at all forecast times. This is true for both the dependent and independent data sets. The difference between the two data samples is shown by the large degradation of the BPS at 36 h for the independent sample in all three tests. This may again indicate that the independent sample is too small. The scores in Table XVII indicate the decrease in skill as time increases. It is believed that this decrease in skill with respect to time could be lessened to some degree by the inclusion of prognostic EOF fields. This was indicated by Shaffer (1982) as one of the largest drawbacks of the EOF tropical motion forecasting procedure.

The third and simplest method of skill analysis is the percent correctly forecast (PCF) method. Table XVIII lists the PCFs obtained for each test for both the dependent and independent data sets. This table again illustrates the superiority of the P&E test after the initial 36 h time period. Notice again for the small independent data set at 54 h, the EOF method is superior to both of the other methods which is believed to be due to the clustering effect.

TABLE XVIII

Percent Correctly Forecast Events from the Regression Method and Defining Recurvature as a Predictand Exceeding the Climatology Probabilities of Recurvature (A Score of 100 is Perfect)

	Dependent Set			Independent Set		
	PERS	EOFS	P&E	PERS	EOFS	P&E
36 h	77.7	76.0	76.3	72.9	65.3	72.9
54 h	75.3	71.3	78.2	72.1	76.7	72.1
72 h	71.6	63.8	72.7	71.1	68.4	76.3

This simple method of testing skill was included as an attempt to compare the three tested procedures against the models currently being used by JTWC Guam for guidance. The discussion and comments pertaining to the results of the model comparisons are included in Appendix A.

VI. CONCLUSIONS AND JUSTIFICATION FOR CONTINUED RESEARCH

Elsberry (1979) discusses the inherent problems and advantages of dynamic tropical cyclone models. He states that the lack of vertical and horizontal resolution in the models, as well as a poor understanding of the environmental processes that occur in the vicinity of a tropical storm, are limiting the progress toward more accurate forecasts. Although nested grid models (Harrison, 1981; Harrison and Fiorino, 1982) have been used to improve the resolution, there continue to be problems of data acquisition on the scales of interest. This problem has no solution in the immediate or extended time frames, which necessitates the need for other reliable and less costly methods.

The application of a linear regression scheme to a statistical model using a combination of persistence-related parameters and an EOF representation of the synoptic forcing was completed. The combination of these two types of parameters have shown to be superior for forecasting tropical cyclone recurvature as defined.

The main attributes of the EOF approach to forecasting tropical cyclone recurvature and motion (Shaffer,1982) must again be stressed:

- The method is extremely inexpensive;
- The forecasts can be done on a handheld programmable calculator;
- The method has been shown to be more accurate for forecasting recurvature than persistence and synoptic parameters alone; and
- The method has shown to give superior forecasts when compared to the official JTWC forecasts using the analysis of the 500 mb fields (Shaffer, 1982).

It is believed that the inclusion of prognostic synoptic fields, as suggested by Shaffer (1982), would improve the percentage of the explained variance of the predictand. This would also be reflected as giving better results for the recurvature study described here.

An independent operational evaluation of the schemes presented here needs to be done to determine the validity of the method.

The definition of recurvature needs to be modified. A tropical storm moving 314° is considered as a non-recurvature case where a storm moving 316° is considered a recurvature case. Probabilities of recurvature based on the departure of the tropical cyclone from a forecast track

or a straight line could be utilized instead of using a binary definition as done in this research.

It is understood that the application of new and superior methods of forecasting tropical cyclone recurvature and motion should be questioned. It is believed that this change of methodology (ie, using an EOF representation of the synoptic fields), if adopted, will improve the image of the military weather services by being a positive pioneering effort in an area that has been stagnant for many years.

APPENDIX A

MODEL COMPARISONS

A. PURPOSE

The purpose of this section is to supply the Western Pacific tropical cyclone forecaster with information on the various guidance techniques for forecasting tropical cyclone motion, and, in particular, their reliability in forecasting recurvature. The definition of recurvature (Leftwich, 1978,1982) is similar as described earlier except for the northeastward motion during the 24 h (vice 12) prior to the end of the forecast period. This modification was done to accomodate the forecast warning verification times which are 24, 48 and 72 h.

> "Recurvature is a net displacement northward of 315° during the forecast period or the attaining of northeastward motion during the 24 hours prior to the end of the forecast period.

B. THE DATA

The data analyzed were assembled by Dr. Ted Tsui of the Naval Environmental Prediction Research Facility (NEPRF) during the 1979-1981 Northwest Pacific typhoon seasons. The data were the best track information from the tropical

disturbance stage through the entire life cycle of each of the 28 storms of 1979 and 1980 and the 29 storms of 1981. Also included were the 24, 48 and 72 h positions of 12 tropical cyclone forecast aids available at JTWC. Seven of these aids and the Joint Typhoon Warning Center official forecasts are evaluated below with respect to the recurvature decision.

C. MODEL DESCRIPTIONS COMPARISON TESTS

The following paragraphs are descriptions of the objective forecast aides currently being used at JTWC. The descriptions have been taken from the 1981 Annual Tropical Cyclone Report. All JTWC objective techniques, except those involving dynamic models, are executed using operational data available prior to warning times (00GMT and 12GMT). These dynamically-based objective aids are usually received at JTWC within 2 to 5 hours of a specific warning time.

An analogue methcd, abbreviated TOP5, provides three movement and intensity forecasts. These three forecasts are for analogues of straight-moving cyclones, of recurving cyclones and a combination of analogues including straight, recurving, and all other cyclones that do not meet the specific cirteria of those two categories.

An extrapolation technique, abbreviated XTRA, provides a track connecting the 12-h old preliminary best track position and the current warning position, which is then extrapolated to 24 and 48 h. HPAC, which is a combination of XTRA and a climatological aid, provides a forecast of the track and intensity changes based on the initial position of the system. The climatological data base includes the period from 1945 to 1973. The (BPAC) forecasts are based on blending the past motion of the tropical cyclone with the climatology forecast positions. This program requires only a Texas Instrument (TI-59) calculator to generate 12 to 72 h forecast positions. The blending routine gives less weight to persistence at each succeeding forecast interval.

An updated version of the HATRACK/MOHATT steering program (now called CYCLOPS and designated as CY50 for the 500 mb level) can provide steering forecasts at many different levels. The program can be run in the modified (includes a 12-h persistence bias) or unmodified versions applied to either analysis or prognostic fields. The program advects a point vortex on a pre-selected analysis and/or smoothed prognostic field at designated levels in 6-h time steps through 72 h. In the modified version, the

program uses the previous 12-h history position to compute the 12-h forecast error and applies a bias correction to the forecast positions. In 1981, only the modified version, in the prognostic mode for the 500 mb level was verified.

The dynamic Tropical Cyclone Model (TCMO) is a coarse mesh (220 km) primitive equation model. The digitized cyclone warning position is bogused into the 850 mb wind and temperature fields of the FNOC global band analysis. Hemispheric model forecast data are used on the boundaries. Two versions are currently run: One runs from forecast fields and is available on an automatic request basis, and the other is initialized on the analysis fields noted earlier. The model based on the analysis fields was tested in this study.

The NTCM or "nested" primitive equation tropical cyclone model is initialized on FNOC 12-h forecast fields. The model covers a limited, but relocatable, tropical domain with three layers in the vertical. The finer scale, or "nested" grid, covers a 1200 km square area with a 41 km grid spacing and moves to keep a 850 mb vortex in its center. This model is integrated with a coarse channel model grid with a grid spacing of 205 km over a 6400 by 4700

km domain. Once initialized, the model runs independent of the remaining FNOC forecast fields. The NTCM is available via automatic request for 00 and 12 GMT forecast fields only.

D. SCREENING PROCEDURE FOR MODEL TESTING

Several different requirements were taken into consideration for inclusion in this comparison study that were not considered for the EOF analysis scheme. Inclusion was based on:

- Using the 'best track' past zonal and meridional displacements (after the initial 12 h of the track) vice the past warning displacements used in the EOF study, to test for eastward displacement (not considered case);
- Pseudo-independence is again assumed by requiring time separations of 36 h within the same storm;
- A 30 h past history was not required;
- All tropical cyclones were included, rather than just tropical storms and typhoons; and
- All storms north of the equator, vice 10° north, were included.

Table XIX lists the 24, 48 and 72 h recurvature probabilities for the three year sample. When compared to the corresponding values of the sample climatology listed in Table II, the difference between the inclusion criteria become evident. The inclusion of the tropical depressions

in the area south of 10° north is the largest contributor to the lower values of recurvature probability. A high annual variability is indicated in this small sample. There is generally a slow increase of probability of recurvature with time as was the case in Table II.

TABLE XIX

Number of Recurving (rcv), Non-recurving (nrcv), and Probability of Recurvature (prob) for Tropical Cyclone Seasons 1979, 1980 and 1981.

	1979			1980			1981		
tau	rcv	nrcv	prob	rcv	nrcv	prob	rcv	nrcv	prob
24	39	94	.293	36	78	.316	26	73	.263
48	41	84	.328	35	65	.350	23	63	.267
72	25	81	.236	29	53	.354	21	52	.288

The HSS for the three separate years are listed in Table XX. The HSS in this data set remains as described earlier with a slight modification. This difference is that the verification of the model's predicted recurvature is based entirely upon the predictands matching the actual recurvature criteria as defined. There is no climatological threshhold that is set for inclusion as a recurvature or non-recurvature as was the case for the earlier data sample.

Again, the most noticable feature of the table is the general decrease of skill with respect to time. The

exception to this generality is the BPAC model performance for 1979 and the TCMO model for 1981 where the HSS increased with time. An interesting comparison can be shown when comparing JTWC with the TCMO forecast aids for 1981. There is a definite correlation between TCMO and JTWC. This is an indication of JTWC following the guidance of this dynamic model quite closely in the extended time frames.

Table XXI lists the BPS for the three time periods of interest. The BPS forecast predictands in this case are not on the interval between 1.0 and 0.0, but are identically equal to 1.0 or 0.0. Any knowledge of a comparison of BPS results using a continuous predictand as compared to a binary predictand scheme is available. Comparison of the common time period of 72 h between the two entirely independent data sets of different sizes therefore has little meaning. The BPS of the TCMO model in 1981 and BPAC for 1979 are the only models that approach the BPS for the combination of EOFS and Persistence in the earlier study. A general trend toward larger BPS are prevalent for all years for most of the forecast aids.

Comparison of the PCF values indicated in Table XXII, and the HSS reveals the similarity of the two skill scores.

TABLE XX

Heidke Skill Score for Models for 1979, 1980, and 1981 (A Score Of 1.0 is Perfect, and a (*) Indicates too Few Cases to be Ranked)

Model results for 1979

	HPAC	TCMO	JTWC	TOP5	CY50	BPAC	XTRA	NTCM
24 h	.449	.621	.424	.296	.388	.403	.304	.167
cases	421	95	427	247	304	345	425	12
rank	(2)	(1)	(3)	(7)	(5)	(4)	(6)	(*)
48 h	.457	.506	.355	.230	.426	.568	.235	.667
cases	368	81	363	228	265	296	371	12
rank	(3)	(2)	(5)	(7)	(4)	(1)	(6)	(*)
72 h	.381	.391	.347	.266	.095	.586	.072	.667
cases	252	69	288	199	210	251	304	12
rank	(3)	(2)	(4)	(5)	(6)	(1)	(7)	(*)

Model results for 1980

	HPAC	TCMO	JTWC	TOP5	CY50	BPAC	XTRA	NTCM
24 h	.518	.621	.424	.296	.388	.403	.304	.167
cases	419	73	412	353	364	361	373	62
rank	(2)	(1)	(3)	(7)	(5)	(4)	(6)	(8)
48 h	.313	.406	.418	.461	.411	.453	.301	.387
cases	352	64	347	304	309	300	306	62
rank	(7)	(5)	(3)	(1)	(4)	(2)	(8)	(6)
72 h	.004	.378	.089	.112	.273	.217	.164	.309
cases	261	45	257	245	245	240	225	55
rank	(8)	(1)	(7)	(6)	(3)	(4)	(5)	(2)

Model results for 1981

	HPAC	TCMO	JTWC	TOP5	CY50	BPAC	XTRA	NTCM
24 h	.462	.457	.542	.466	.567	.480	.483	.333
cases	383	129	384	348	282	377	383	156
rank	(6)	(7)	(2)	(5)	(1)	(4)	(3)	(8)
48 h	.298	.574	.515	.333	.489	.388	.255	.289
cases	325	108	309	297	235	320	325	135
rank	(6)	(1)	(2)	(5)	(3)	(4)	(8)	(7)
72 h	.013	.647	.540	.021	.304	.063	.149	.196
cases	235	68	268	235	181	254	235	107
rank	(8)	(1)	(2)	(7)	(3)	(6)	(5)	(4)

The rankings of these two methods are the same for 51 of 69 comparisons.

TABLE XXI

Brier P - Score Statistics for 24, 48 and 72 h Models for 1979, 1980 and 1981 (A Score of 0.0 is Perfect, and a (*) Indicates too Few Cases to be Ranked)

Model results for 1979

	HPAC	TCMO	JTWC	TOP5	CY50	BPAC	XTRA	NTCM
24 h	.570	.379	.576	.704	.612	.597	.696	.833
cases	421	95	427	247	304	345	425	12
rank	(2)	(1)	(3)	(7)	(5)	(4)	(6)	(*)
48 h	.543	.494	.645	.702	.574	.432	.765	.333
cases	368	81	363	228	265	296	371	12
rank	(3)	(2)	(5)	(6)	(4)	(1)	(7)	(*)
72 h	.619	.609	.653	.734	.905	.414	.928	.333
cases	252	69	288	199	210	251	304	12
rank	(3)	(2)	(4)	(5)	(6)	(1)	(7)	(*)

Model results for 1980

	HPAC	TCMO	JTWC	TOP5	CY50	BPAC	XTRA	NTCM
24 h	.482	.493	.461	.465	.440	.454	.536	.581
cases	419	73	412	353	364	361	373	62
rank	(5)	(6)	(3)	(4)	(1)	(2)	(7)	(8)
48 h	.688	.594	.582	.539	.589	.547	.699	.613
cases	352	64	347	304	309	300	306	62
rank	(7)	(5)	(3)	(1)	(4)	(2)	(8)	(6)
72 h	1.004	.622	.911	.873	.727	.783	.836	.691
cases	261	45	257	245	245	240	225	55
rank	(8)	(1)	(7)	(6)	(3)	(4)	(5)	(2)

Model results for 1981

	HPAC	TCMO	JTWC	TOP5	CY50	BPAC	XTRA	NTCM
24 h	.538	.543	.458	.534	.433	.520	.517	.667
cases	383	129	384	348	282	377	383	156
rank	(6)	(7)	(2)	(5)	(1)	(4)	(3)	(8)
48 h	.702	.426	.485	.667	.511	.612	.745	.711
cases	325	108	309	297	235	320	325	135
rank	(6)	(1)	(2)	(5)	(3)	(4)	(8)	(7)
72 h	.987	.353	.460	.979	.696	.937	.902	.804
cases	235	68	268	235	181	254	235	107
rank	(8)	(1)	(2)	(7)	(3)	(6)	(5)	(4)

TABLE XXII

Percent Correct Forecast Statistics for Models for 1979, 1980 and 1981 (A Score Of 100 is Perfect, and a (*) Indicates too Few Cases to be Ranked)

Model results for 1979

	HPAC	TCMO	JTWC	TOP5	CY50	BPAC	XTRA	NTCM
24 h	71.5	81.1	71.2	64.8	69.4	70.1	65.2	58.3
cases	421	95	427	247	304	345	425	12
rank	(2)	(1)	(3)	(7)	(5)	(4)	(6)	(*)
48 h	72.8	75.3	67.8	64.9	71.3	78.4	61.7	83.3
cases	368	81	363	228	265	296	371	12
rank	(3)	(2)	(5)	(6)	(4)	(1)	(7)	(*)
72 h	69.0	69.6	67.4	63.3	54.8	79.3	53.6	83.3
cases	252	69	288	199	210	251	304	12
rank	(3)	(2)	(4)	(5)	(6)	(1)	(7)	(*)

Model results for 1980

	HPAC	TCMO	JTWC	TOP5	CY50	BPAC	XTRA	NTCM
24 h	75.9	75.3	76.9	76.8	78.0	77.3	73.2	71.0
cases	419	73	412	353	364	361	373	62
rank	(5)	(6)	(3)	(4)	(1)	(2)	(7)	(8)
48 h	65.6	70.3	70.9	64.9	70.6	72.7	69.3	69.4
cases	352	64	347	304	309	300	306	62
rank	(7)	(4)	(2)	(8)	(3)	(1)	(6)	(5)
72 h	49.8	68.9	54.5	63.3	63.7	60.8	64.0	65.4
cases	261	45	257	245	245	240	225	55
rank	(8)	(1)	(7)	(5)	(4)	(6)	(3)	(2)

Model results for 1981

	HPAC	TCMO	JTWC	TOP5	CY50	BPAC	XTRA	NTCM
24 h	73.1	72.9	77.1	73.3	78.4	74.0	74.2	66.7
cases	383	129	384	348	282	377	383	156
rank	(6)	(7)	(2)	(5)	(1)	(4)	(3)	(8)
48 h	64.9	78.7	75.7	66.7	74.5	69.4	62.8	64.4
cases	325	108	309	297	235	320	325	135
rank	(6)	(1)	(2)	(5)	(3)	(4)	(8)	(7)
72 h	50.6	83.4	77.0	51.1	65.2	53.1	54.9	59.8
cases	235	68	268	235	181	254	235	107
rank	(8)	(1)	(2)	(7)	(3)	(6)	(5)	(4)

E. SUMMARY

Seven forecast aids used by Joint Typhoon Warning Center (JTWC) Guam, were tested for ability to forecast tropical cyclone recurvature at 24, 48 and 72 h.

Using the skill scores described in Chapter V for the 1979-81 typhoon season, model performance indicates a large annual variation of skill between the models.

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